A MIXED-GAS CONTROL SYSTEM FOR AN ENVIRONMENTAL CHAMBER

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In order to simulate the expected environmental conditions in a submarine that has become disabled (i.e. loss of electrical power and subsequent inability to control temperature, humidity, and oxygen and carbon dioxide levels), a system was created to control the oxygen and carbon dioxide concentration of an environmental chamber. The study protocol called for a baseline testing period of ambient environmental conditions for 2 days (20 C, 50% RH, 20.93% O_2, 0.04% CO_2), followed by a 24-hour transition phase to the disabled conditions (4 C, 80% RH, 16.75% O_2, 2.50% CO_2), which where maintained for 5 days. Due to numerous design factors, the hypobaric chamber facility was chosen to conduct this study, since the facility met all of the needs of the study except for the ability to control oxygen and carbon dioxide levels, which none of the institute's chambers are normally capable of. Reduced oxygen content was achieved by displacement with nitrogen, and increased carbon dioxide content was achieved by injection of 100% carbon dioxide and metabolic carbon dioxide production. The oxygen and carbon dioxide content of the chamber was continually monitored and controlled by a custom designed software system.

During the 5 day "disabled" portion of the study, chamber conditions were as follows: temp $4.51 \pm 0.56°$ C; relative humidity 80.48 ± 5.27 % RH; oxygen $16.73 \pm 0.06\%$ and carbon dioxide $2.49 \pm 0.04\%$. Variations in temperature, oxygen and carbon dioxide levels, as indicated by the standard deviation, were all within desired limits ($\pm 1.0°C$; ± 0.10 % concentration). Relative humidity was outside the desired limit of $\pm 3.0\%$ R

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

EXECUTIVE SUMMARY

In order to simulate the expected environmental conditions in a submarine that has become disabled (i.e., loss of electrical power and subsequent inability to control temperature, humidity, and oxygen and carbon dioxide levels), a system was created to control the oxygen and carbon dioxide concentration of an environmental chamber. The study protocol called for a baseline testing period of ambient environmental conditions for 2 days ($20°C$, 50% RH, 20.93% O_2, 0.04% CO_2), followed by a 24-hour transition phase to the disabled conditions ($4°C$, 80% RH, 16.75% O_2, 2.50% CO_2), which were maintained for 5 days. The hypobaric chamber facility was chosen for this study because it met all of the needs of the study except for the ability to control oxygen and carbon dioxide levels, which none of the institute's chambers are normally capable of doing. Reduced oxygen content was achieved by displacement with nitrogen, and increased carbon dioxide content was achieved by injection of 100% carbon dioxide and metabolic carbon dioxide production. The oxygen and carbon dioxide content of the chamber was continually monitored and controlled by a custom designed software system.

During the 5 day "disabled" portion of the study, chamber conditions were as follows: temp $4.51\pm0.56°C$; relative humidity $80.48\pm5.27\%$ RH; oxygen $16.73\pm0.06\%$ and carbon dioxide $2.49\pm0.04\%$. Variations in temperature, oxygen and carbon dioxide levels, as indicated by the standard deviation, were all within desired limits ($\pm1.0°C$; $\pm0.10\%$ concentration). Relative humidity was outside the desired limit of $\pm3.0\%$ RH.
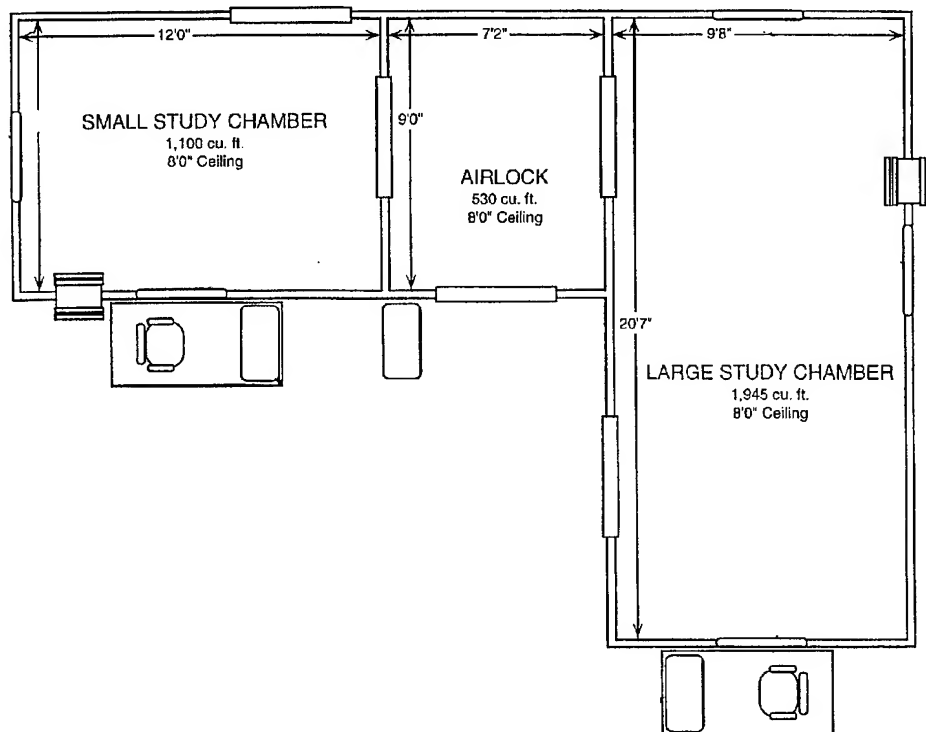
INTRODUCTION

Typically, the USARIEM Hypobaric Chamber Facility is utilized for altitude simulation studies, as its name implies. However, since the facility is capable of precise temperature and humidity control, it can also be used for environmental studies. Recently, the Naval Medical Submarine Research Laboratory (NMSRL) contacted USARIEM wishing to study the physiological effects of the environment inside a submarine under disabled conditions (i.e., loss of electrical power and subsequent inability to control temperature, humidity, and carbon dioxide and oxygen levels). The purpose of this technical note is to describe the basic characteristics of the chamber as it applies to this study, and to describe the control system that was created to maintain an atmosphere consisting of 16.75% O_2, 2.5% CO_2, and balance N_2.

GENERAL CHAMBER DESCRIPTION

Due to its large size (total volume ~3600 ft.^{3}) and built-in bathroom facility, the hypobaric chamber is well suited for studies involving prolonged human habitation. For this study, the subjects lived in the chamber for 11 days. The airlock situated between the large and small study chambers allows for rapid ingress and egress of investigators and staff. It also acts as a buffer zone, helping to maintain the experimental environment. Figure 1 shows the layout and dimensions of the altitude chamber facility.

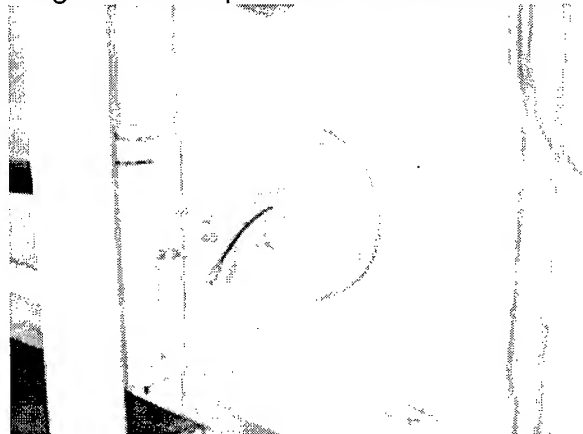Figure 1. Overview of USARIEM's Hypobaric Chamber Facility

The chamber has numerous built-in electrical penetration panels and assorted airtight penetration ports through the chamber walls (Figures 2 and 3), which allow easy connection of gas input and room air analysis lines. The chamber environmental control system is capable of temperature control from −32 to 43°C, ±1°C and humidity control from 20%-80% RH, ±3% RH. We wanted to operate the chamber within system specifications, and to create a mixed-gas control system capable of maintaining an atmosphere ±0.10% of desired levels. For the "disabled submarine" portion of this study, the chamber was operated at 4°C and 80% RH. Pre and post-exposure testing conditions were 22°C and 50% RH. Temperature control is accomplished by circulating ethylene glycol refrigerant through tempering coils located in a plenum above the ceiling of each chamber. The plenum air volume is part of the internal volume of the chamber, and air movement thru the plenum is separate from outside fresh air ventilation. The temperature programmable logic controller will allow either a hot or cold supply of glycol (located in separate ~200-gallon tanks) to flow into the chamber common glycol tank and the tempering coils until the control setpoint has been reached. Air from inside the chamber is circulated over the coils and into the chamber through diffusion panels in the ceiling designed to minimize the effects of air velocity and noise. The temperature control loop is a closed loop (i.e., there is no movement of air in or out of the chamber). In the small study chamber, the entire volume of air passes over the tempering coils every ~45 sec, and in the large chamber every ~90 sec. Relative humidity is decreased by chilling the air to condense the water vapor and then reheating the dried air to maintain the desired temperature. Increased RH is achieved by injection of steam into the temperature control plenum above the chamber. Fresh air is metered into the plenum above each chamber and into the airlock via a separate set of controls and valves.

The large and small study chambers have independent environment and pressure (altitude) controls, allowing different conditions to be maintained simultaneously in each area. During the protocol for which this mixed-gas control system was developed, volunteers lived in the large study chamber for the majority of the time. Thus, results reported here are for conditions inside that chamber. Additional testing of the volunteers took place in the small study chamber before, during, and after

Figure 2. Electrical Penetration Port

Figure 3. Sample Line Penetration Port

the "disabled submarine" portion of the protocol. During the thermoregulatory tests in the small study chamber, the oxygen and carbon dioxide were maintained at the levels established in the large chamber, while temperature and RH were varied according to the needs of the experimental protocol. Due to these variances, chamber conditions for the small study chamber are not reported here. The airlock is not environmentally controlled and will equilibrate to whichever chamber it is open to. In order to help maintain a consistent, controlled, inside atmosphere, a plastic strip warehouse type curtain was installed inside the airlock door, and all chamber ingress and egress occurred thru that door. In theory, this would help reduce the influx of outside air whenever the airlock door was opened.
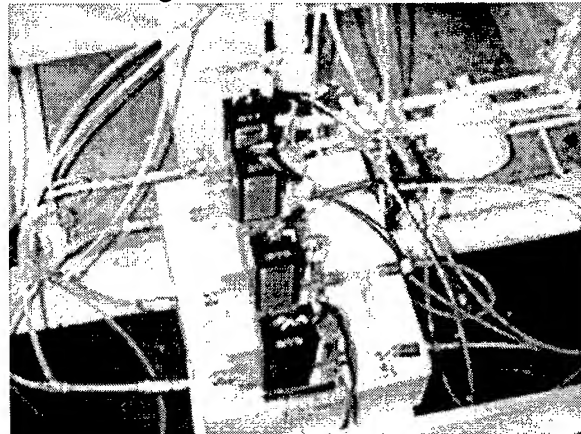
MIXED-GAS CONTROL SYSTEM

In order to reach the desired 16.75% O_2 level, nitrogen was bled into the chamber in order to displace the oxygen. Due to the large volume of nitrogen needed to decrease the O_2 content (~35,000 ft^3 for the duration of the study) and the length of the study, liquid nitrogen cylinders were utilized. Cylinders containing 100% CO_2 were used in combination with expired CO_2 to increase the chamber CO_2 content to 2.5%. Three cylinders of gas where connected to a manifold and pressure regulator, whose output was set at 30 PSI. Separate manifolds were used for each gas (Figure 4). The use of a manifold allowed for a continuous supply of gases, even when empty cylinders were being replaced. The flow of gases passed through Sierra Instruments Model 860 flowmeters, which were controlled by a Sierra Instruments Model 904C flo-box, which was controlled in turn by Hewlett-Packard instrumentation and software described below. The flowmeters are capable of a flow rate of 0-100 standard liters per minute (slpm). Each manifold led to 2 flowmeters, one each for the small and large study chambers (Figure 5). The output from the flowmeters was injected into the tempering plenum above each chamber, ensuring that the gases were well mixed as they passed through the ceiling diffusion panels. Because a rapid decrease in inspired O_2 was desired initially (20.93-16.75% F_iO_2 as rapidly as possible), a T-fitting was installed in the line between the nitrogen gas manifold and the flowmeter, with the output from the T leading directly into the chamber tempering plenum.

Figure 4. Manifolds and Cylinders

Figure 5. Flowmeters

Flow through this line was considerably greater than the 100 liter per minute limit of the flowmeters and was controlled via a manual control valve.

The continuous fresh air ventilation rate was maintained at 10 ft^3 per minute or lower. This ventilation rate was adequate to prevent the inspired O_2 percentage from dropping below 16.75%. However, the ventilation rate was not high enough to compensate for CO_2 increases due to metabolic production, so CO_2 absorptive material was utilized. Calcium carbonate was placed in a large container with a wire mesh bottom and a plexiglass top with a fan installed. When the fan was on, it drew air up through the calcium carbonate and decreased the CO_2 concentration (Figure 6). A total of 4 CO_2 scrubbers were utilized throughout the chambers. The calcium carbonate turned from white to blue as it became saturated with CO_2, and was replaced with fresh calcium carbonate as necessary.

Chamber conditions were monitored via a setup typically used for analysis of expired air (Figure 7). Ametek S-3A/I oxygen analyzers and Beckman LB-2 carbon dioxide analyzers were placed outside each chamber, and sample air was drawn from 3 separate locations inside each study chamber, to ensure a representative sample of the room air. With the exception of those times when the analyzers were calibrated (every 4 hours), approximately 500mL/min were drawn continuously from each chamber. Output signals, proportional to the concentrations of O_2 and CO_2 in each chamber, were used by the controller software that is described in the following section.

Each of the components described above were monitored and controlled by a custom designed data acquisition and control system. Hewlett-Packard VEE (Visual Engineering Environment) software was used to write a program which included separate subroutines for each phase of the experiment. These phases were:
Rapid O_2 decrease (20.94%→16.75%), CO_2 constant (0.04%)
Acute Hypoxia: O_2 = 16.75%, CO_2 = 0.04%
Gradual CO_2 increase (0.04%→2.5%), O_2 constant (16.75%)
Steady State DISSUB: O_2 = 16.75%, CO_2 = 2.5%
Gradual CO_2 decrease (2.5%→0.04%), O_2 constant (16.75%)
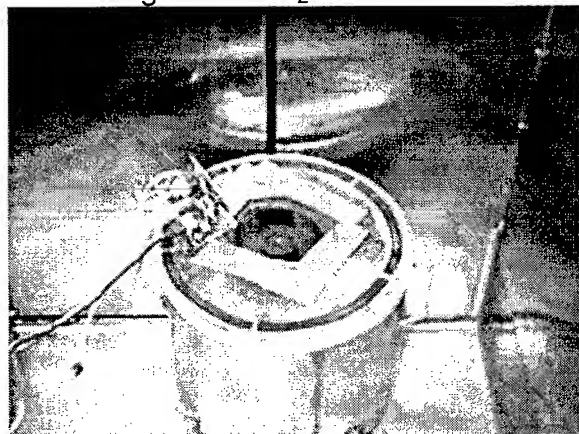Chronic hypoxia:O_2 = 16.75%, CO_2 = 0.04%

Figure 6. CO_2 scrubber

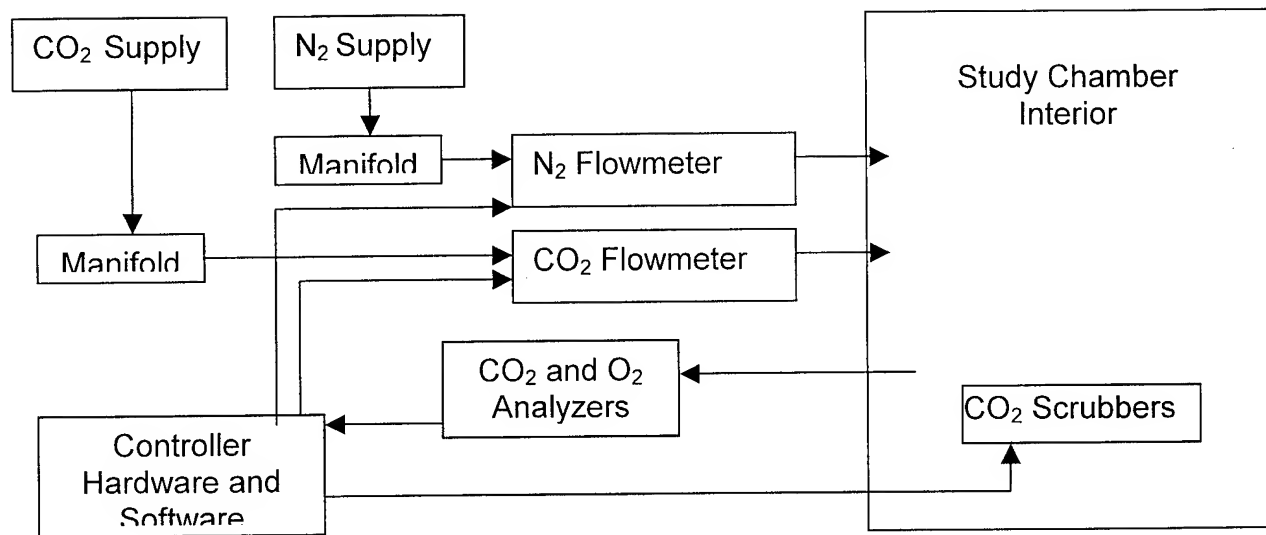Figure 7. Analyzers and control computer

Based on physiological predictions and preliminary testing, feedback loops were set up for each required transition or steady state atmosphere, relying primarily on proportional control of the CO_2 and N_2 flowmeters. The constants were different for the separate chambers and were global variables that could be modified during the course of the experiment for fine-tuning purposes. Every 10 secs (except during calibration of the O_2 and CO_2 sensors), the gas concentrations were checked by the program, and the appropriate adjustment, if any, was made automatically.

HP-VEE software was installed on a Pentium PC with an HP-IB board (model 82341) to communicate with an HP3852A Data Acquisition and Control Unit. Several types of components were installed in the back plane of the HP3852A. Twenty channel relay multiplexers (HP44705A) accepted inputs from the gas analyzers and the CO_2 scrubbers. These voltages were measured by a high speed, high precision, integrating voltmeter (HP44701A). Digital to analog converters (HP44727A/B/C) provided power to turn on the fans in the CO_2 scrubbers and carried voltages to the Sierra Instruments Model 904C flo-box that controlled rates of flow in the individual flowmeters. While there was a slight lag in the sampling of the chamber air (<20 sec) due to the lengths of tubing leading to the analyzers, the regulation of the flowmeters and scrubber fans was nearly instantaneous.

The program was written to step through the subroutines according to the experimental protocol timeline. It was possible to override this schedule, without disrupting program execution, if necessary. In addition to maintaining environmental conditions, safety features were incorporated throughout the program. Graphic and digital displays of O_2 and CO_2 concentrations in each study chamber were visible on the screen at all times. The user could call up additional information on valve positions and trend information as required. Alarms were included to alert observers to impending or actual harmful concentrations of gases inside the chamber. Different levels of audible and visual alarms were included in accordance with the limits set by the medical staff. Increasing levels of potential risk were accompanied by louder and more obvious alarms. The alarms were loud enough during unoccupied chamber testing to attract the attention of anyone in the vicinity of the chamber facility. Reminders to calibrate the analyzers and to change Drierite, gas cylinders, and CO_2 absorbing material were included but never necessary. A rotating schedule of chamber operating staff were on-duty at all times during the study to monitor chamber conditions, control computer operation, gas cylinder status, CO_2 absorbing material and to calibrate the gas analyzers every 4 hours. Figure 8 shows a schematic layout of the mixed-gas control system for a single chamber.

Figure 8. Mixed-gas control system schematic

SYSTEM PERFORMANCE

Chamber conditions throughout the study are summarized in Table 1. During the pre- and post-cold exposure portions of the protocol (days 0a thru 2 and days 10 and 11), desired chamber conditions were 21°C and 50% RH. The actual conditions during this time were 21.16±.83° C, 51.19±4.51% RH. The temperature conditions were within the ±1.0°C maximum desired variability, and humidity was slightly outside the desired ±3.0% RH variability. During the cold exposure portion (days 2 thru 7), desired conditions were 4°C and 80% RH. Actual conditions were 4.51± .56°C and 80.48±5.27% RH. Again, temperature conditions were within and humidity conditions were slightly outside the desired maximum variability.

Conditions during the hypoxic and hypercapnic portion of the study (days 2 thru 7) were as follows: 16.73±0.06% O_2 and 2.49±0.04% CO_2. These values where within the ±0.10% variability desired by the principle investigators. The acute and chronic hypoxia phases were also with the desired variability limits.

DISCUSSION AND FUTURE RECOMMENDATIONS

This technical report describes the development and performance of a system to create and control a mixed-gas atmosphere in an environmental chamber. With the exception of humidity, each of the controlled variables was maintained within the limits desired by the study investigators. The larger-than-desired deviations in humidity levels may be the result of several factors. One factor is the design of the environmental

Table 1. Chamber Conditions by Study Phase.

PHASE	Control	Acute Hypoxia	First Transition	Steady-State "DISSUB" Conditions	Second Transition	Chronic Hypoxia
Day and Time	Days 0a and 0b	0700-1500 Day 1	1500 Day 1 to 1500 Day 2	1500 Day 2 to 1900 Day 7	1900-2400 Day 7	Days 8 and 9
% F_iO_2	* (20.93)	16.77±0.03 (16.75)	# (16.75)	16.73±0.06 (16.75)	# (16.75)	16.76±0.02 (16.75)
%F_iCO_2	* (0.04)	0.44±0.14 (0.04)	# (0.04-2.50)	2.49±0.04 (2.50)	# (2.50-0.04)	0.18±0.08 (0.04)
% RH	50.42±5.18 (50)	50.69±4.79 (50)	# (50-80)	80.48±5.27 (80)	# (80-50)	50.74±2.94 (50)
°C T_{air}	22.2±1.12 (22)	19.49±0.76 (220	# (22-4)	4.51±0.56 (4)	# (4-22)	21.2±0.82 (22)

Mean±standard deviation (setpoint)

* These are normal ambient conditions, which were monitored but not recorded, as the chamber doors were open during this phase of the study.

Mean and standard deviations are not reported here, as conditions were continually changing to and from the indicated values.

control system. As noted in the introduction, the chamber is capable of controlling humidity from 20%-80% RH, ±3% RH. Increases in RH are accomplished by injection of steam (water vapor) into the chamber and are easily controlled over a wide RH range. Decreases in RH, on the other hand, are accomplished by air flowing over dehumidification coils, the temperature of which is controlled by a microprocessor. The lower the temperature of the coils relative to the air passing over them, the greater the dehumidification. A side effect of running a cold air study is a corresponding decrease in the ability to control humidity, due to the decreased temperature differential between the air and the dehumidification coils. Had the study been conducted at a higher air temperature, a greater degree of humidity control would have been realized. In an effort to examine the effect of frequent ingress and egress of study personnel, and their presence in the chambers for an extended period of time, humidity conditions during the day and overnight were compared. From midnight to 0500 hrs, on 3 different nights, the humidity was 81.89±2.51% RH. Comparitively, during the daytime on the same days, the humidity was 82.47±4.40% RH. Clearly, the variations in humidity control were the result of more personnel inside the chamber and the associated effect of frequent ingress and egress. These discussions are academic, however, because the physiological effects of this humidity variation are negligible due to the conditions under

which this study was conducted (R. Gonzalez, personal communication, March 2001). Humidity variations less than 10% are not sensed by the skin and, therefore, the desire to control humidity to within 3% was unnecessarily strict.

Should the occasion arise to conduct another mixed-gas study in an environmental chamber, there are several improvements to the system that could be made. For instance, there are commercial gas analyzers available that are more stable and require less frequent and less time for calibration than those used for these tests. Additional analyzers and flowmeters would make it possible to control other gases in the test chamber such as carbon monoxide. System performance could also be improved by incorporating knowledge gained into the proportional integral derivative constants for the control system. Due to limited chamber time for pilot testing and uncertainty about oxygen requirements and carbon dioxide production under these conditions, the constants in the controlling equations were actually global variables that could be changed as necessary. Lessons learned could be applied to fine-tuning the equations to require fewer (or no) adjustments during the protocol. The CO_2 scrubbers could be made taller and thinner, which would not only reduce the footprint for each, but might also improve removal capacity due to the relative sizes of the canisters containing the scrubbing material and the size of the fan drawing the air through them. Several spare scrubbers should be available to swap into the chamber as the scrubbing material becomes saturated. The used scrubbing material could then be exchanged outside the chamber to minimize problematic dust inside. The control systems were able to simulate environmental conditions on a submarine during normal operation and under disabled conditions within the tolerances required for this protocol. If a protocol had more stringent requirements, additional plastic curtains could be added at the doors separating air lock from test chambers to further minimize outside air incursion as staff members enter and leave the test environment. Alternately, staff could wait in the airlock while conditions equilibrate before entering the test chambers.

This technical note documents the successful creation and operation of a mixed-gas control system for an environmental chamber. Acceptable levels of control were maintained for all variables, with the exception of humidity, for the duration of the study. While improvements could be made, the system performed more than adequately for the study for which it was designed. This system could easily be adapted for other gas concentrations or other gases entirely, with minimal changes to the system. Also, since the main use of the environmental chamber is for altitude studies, it is conceivable that the mixed-gas control system could be modified for use in a hypobaric environment.